DESTRUCTIVE EVALUATION AND EXTENDED FATIGUE TESTING OF RETIRED AIRCRAFT FUSELAGE STRUCTURE: PROJECT UPDATE

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Abstract

In this project, the Federal Aviation Administration (FAA) and Delta Air Lines have teamed in a 3-year effort involving the inspection, teardown destructive evaluation, and extended fatigue testing of fuselage structure removed from a retired passenger aircraft near its design service goal. This paper reports on the first year's activities for this project. Nine large sections were removed from the B727 aircraft representative of fuselage structure susceptible to widespread fatigue (WFD). Detailed inspections using both conventional and newer emerging nondestructive inspection (NDI) methods were made before and after the removal of the sections. Many crack indications were found by NDI conducted along stringer 4R fuselage lap joint. These crack indications were in the hidden lower skin, where, due to their small size, would not be expected to be found under an operator's routine visual maintenance program. Much fewer crack indications were found along the lap joint in stringer 4L. Five sections will be destructively evaluated to characterize the state of multiple-site damage (MSD) and multiple-element damage in fuselage structure. A teardown procedure was developed to disassemble joints and reveal fracture surfaces at fasteners for damage characterization. Preliminary results from teardown destructive examinations from several lower row fastener holes had more than two cracks (some had up to five) emanating from the hole. In the remaining four sections, the state of MSD will be advanced through extended fatigue testing using the FAA's Full-Scale Aircraft Structural Test Evaluation and Research facility and then assessed through teardown destructive evaluation. For this, one panel was prepared and modified consisting of six frames, Body Station (BS) 620 through 720, and six stringers, S-2L through 7L. The panel includes the longitudinal lap joint along S-4L and butt joint along BS-680. Extended fatigue testing will provide data to enable calibration and validation of predictive methodologies for structural fatigue and will serve as a test bed to evaluate the sensitivity and effectiveness of standard and emerging NDI to detect small cracks. The data generated from this project will be used for developing and assessing programs to preclude WFD in the commercial fleet.

Introduction

Airframe teardown inspections and extended fatigue testing are an effective means for structural evaluations and assessments for continued airworthiness of high-time operational aircraft, particularly those approaching their design service goal (DSG). Essential information and data for evaluating airframe structures that are susceptible to widespread fatigue damage (WFD) are obtained from teardown inspections. Amendment 96 to Part 25.571 of Title 14 Code of Federal Regulations requires that it "be demonstrated with sufficient full-scale test evidence that widespread fatigue damage will not occur within the design service goal of the airplane by teardown inspections followed by extended fatigue testing." Corresponding Advisory Circular, AC 25.571-1C, provides general guidelines on the requirements and recommends rigorous posttest teardown inspections as a way to generate sufficient evidence. However, AC 25.571-1C does not specify the teardown protocol, inspection procedures, data collection, and subsequent analyses.

In 1999 the Airworthiness Assurance Working Group (AAWG) published technical recommendations on rulemaking to prevent WFD in the commercial fleet [1]. The AAWG rule-writing group, as tasked by the Federal Aviation Administration (FAA), is currently using those recommendations in developing programs to preclude the occurrence of WFD. The AAWG identified 16 generic types of structure susceptible to WFD. A few examples are shown in Figure 1.

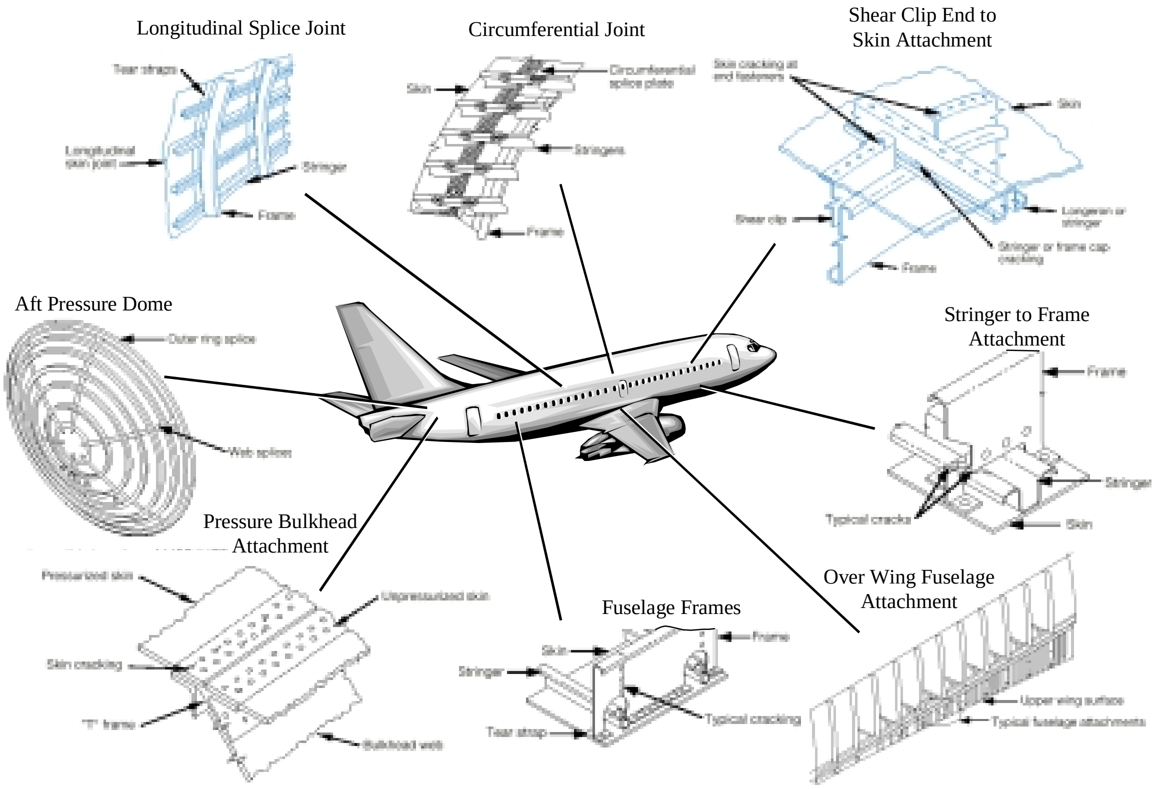

Figure 1. Typical structure susceptible to MSD

As a result of the AAWG recommendations, the FAA plans to issue a Notice of Proposed Rulemaking requiring operators to develop a plan, and eventually a structural maintenance program, to preclude WFD in their fleets for baseline and repaired, altered or modified structure. Teardown destructive inspections and extended fatigue testing can provide key information for developing programs to preclude WFD. While the expertise and knowledge base to conduct teardown inspections are well established by the large commercial airframe original equipment manufacturers (OEM) and military sectors, comprehensive guidelines and data that are documented and available to the broader aviation community are lacking. The destructive testing and analysis of structure removed from retired aircraft will provide the FAA with first-hand knowledge of teardown procedures that may be conducted in support of applications for continued airworthiness certification. Experience and knowledge gained from this destructive analysis will enable the FAA to issue essential rules, policy, and advisory circulars pertaining to the prevention of WFD.

General Technical Tasks

For this initiative, the FAA and Delta Air Lines (DAL) have teamed in a 3-year effort to perform destructive evaluation, inspection, and testing of nine lap-spliced panels removed from a retired B727 narrow-body airplane at or near its DSG. The sections removed are representative of fuselage structure susceptible to WFD identified by the AAWG [1]. The primary focus will be to characterize the state of multiple-site damage (MSD) in the fuselage structure using detailed nondestructive inspection (NDI) and destructive examination. The state of MSD will be advanced through extended fatigue testing using the FAA's Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) facility and then assessed through NDI and destructive evaluation. These tests provide a unique opportunity for researchers to measure the incremental development of WFD from cracks that initiated as the result of revenue service operations. A summary of the first year's efforts is presented in this paper.

Description of Airplane

The aircraft selected for this program was a Boeing 727-232 with serial number 20751, line number 1000, and registration number N474DA, Figure 2. It is a 14 CFR 25 certified aircraft representative of typical 14 CFR 121 revenue-service passenger aircraft currently in the domestic fleet. The airplane was placed into service in 1974 and retired in 1998. During that time, the airplane accumulated 59,497 flight cycles and 66,412 flight hours and is near its DSG. The airplane was retired prior to the issuance of Airworthiness Directive (AD) 99-04-22 mandating inspections and repairs for inner layer cracking of the lap joints of the B727. No inspections and repairs were made on this aircraft per AD 99-04-22.

Figure 2. Aircraft stored at the Southern California International Airport in Victorville, CA

The airplane was owned and operated exclusively by DAL, was well maintained and stored, and has a well-documented and accessible service history, Figure 3. From 1974 to 1993, the aircraft was used in mainline routes where its average flight duration was 1.4 hours and average use per day was 8.3 hours. In 1993, modifications were made to the aircraft, including the installation of engine husk kit and thereafter used for shuttle mission where the average flight duration reduced to 0.7 hours and average use reduced to 3.7 hours. The aircraft was retired to the Southern California International Airport in Victorville CA in 1998 under the care of Southern California Aviation. Throughout the history of the aircraft, the average operating pressure was 8.6 psi.

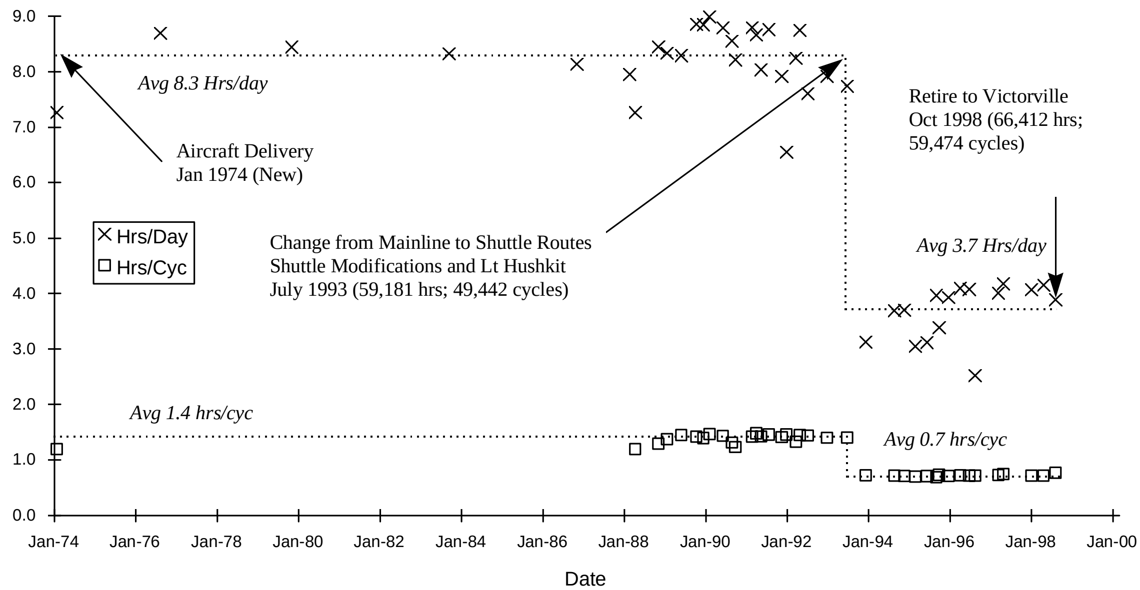

Figure 3. Aircraft utilization history

Target Structure

Nine fuselage lap joint areas susceptible to WFD, each approximately 8 by 12 ft, were removed from the aircraft, five will be destructively evaluated and four will be subjected to extended fatigue testing, Figure 4. Prior to removal, all target sections were labeled with boundaries and identification marks to indicate the location and orientation of the section with respect to the aircraft. In addition,

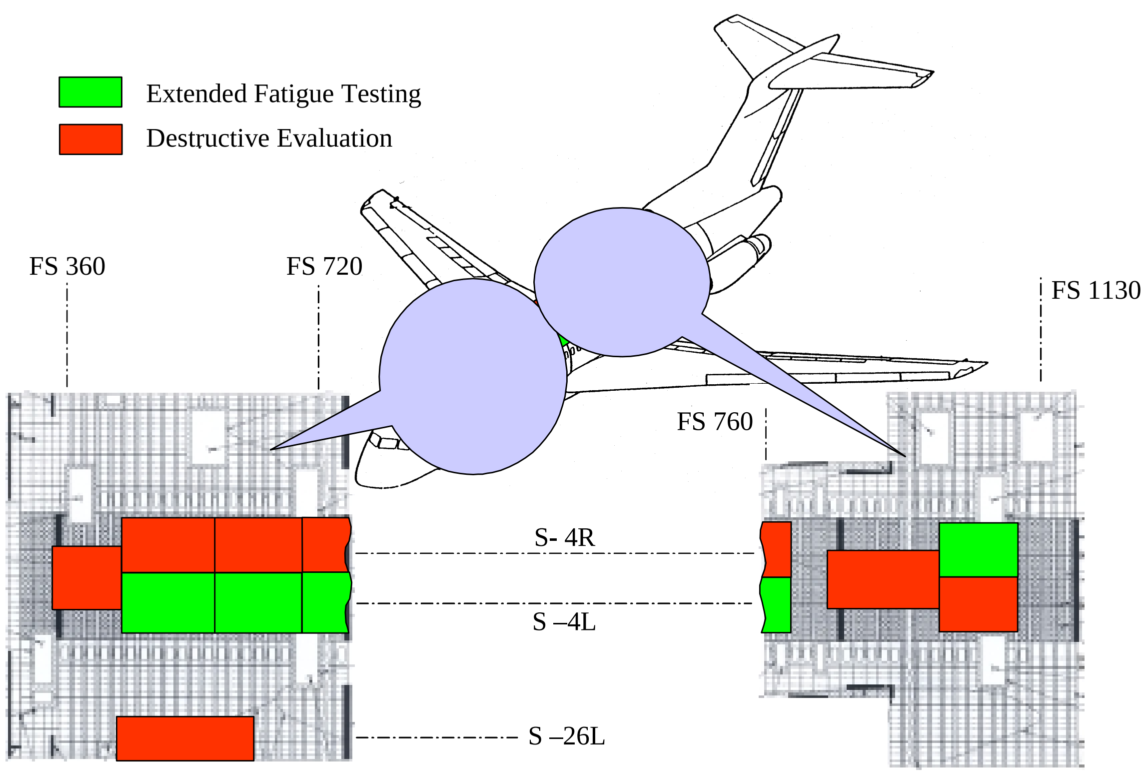

Figure 4. Target structure for test and analysis

weight and balance analyses were conducted in order to properly support the structure as well as to properly define the cutting sequence during removal. Detailed inspections were made before and after the structure was removed, as discussed in the subsequent section. The fuselage lap joint areas were selected to match those called out in AD 99-04-22. Eight of the fuselage lap joint areas are located on the crown of the fuselage along the lap joint at stringer S-4R and -4L between frame stations (FS) 360 and -1130. In this area, a floating frame construction is used with bonded tear straps at the frames designed to force longitudinal cracks to turn circumferentially and flap, preventing the failure from progressing to adjacent bays. One large area located in the bilge of the fuselage along stringer S-26L between FS-360 and -720 will also be examined in this study. In this area, a shear-tied frame construction without tear straps is used. Based on in-service experience findings from fleetwide inspections subsequent to AD 99-04-22, it is anticipated that cracks will be found in the target structure of the selected aircraft.

Detailed Inspections

Prior to removing the target structure, a field inspection was performed at the storage site at the Southern California International Airport in Victorville CA. The purpose of the field inspection was to catalog the condition of the aircraft and target structure. Detailed visual inspections (DVI) and NDI evaluations were conducted using conventional internal Mid-Frequency Eddy Current (MFEC) and external Low-Frequency Eddy Current (LFEC) per standard industry practices, OEM specifications, mandated service bulletins, and ADs. After the target structure was removed and transported to the analysis site at DAL in Atlanta, GA, postremoval inspections were conducted. The methods used in the field inspection were repeated. Results in Table 1 show the distribution of crack indications within the frame stations along the lap joint in stringer S4-R using three conventional approaches, MFEC, LEFC,

Table 1. Number of fasteners with crack indications along stringer S4-R

Frame Stations	Field Inspections			Postremoval Inspections		
	MFEC	LFEC	DVI	MFEC	LFEC	DVI
420-440	1	0	0	1	0	0
440-460	1	0	0	1	0	0
480-500	1	1	0	0	1	0
500-520	3	0	1	7	0	1
520-540	8	4	6	8	4	6
540-560	12	1	10	11	2	10
560-580	6	0	1	12	0	1
580-600	10	0	0	13	0	0
600-620	5	2	3	4	2	0
620-640	5	0	5	6	0	5
640-660	0	0	0	2	0	0
660-680	4	1	0	2	0	0
680-700	1	1	0	1	0	0
700-720	6	0	0	8	0	0
720-720A	9	2	3	9	3	3
720A-720B	8	1	0	8	1	0
720B-720C	13	4	0	14	5	0
720C-720D	4	1	0	5	1	0
720D-720E	3	0	1	3	0	2
720E - 720F	0	0	0	1	0	0
Totals	100	18	30	116	19	28

and DVI. As shown, for both inspections, the MFEC was the most sensitive of the conventional methods. There was good agreement in the results from both inspections. The postremoval inspection was conducted in a laboratory environment with controlled conditions, while the field inspections were done under harsh desert conditions in Victorville, CA.

Several emerging NDI technologies were assessed as part of the postremoval inspections, including magneto optical imaging (MOI), self-nulling rotating eddy-current probe, time varying eddy-current arrays, pulsed eddy current, phased eddy current, eddy-current rotating C-Scan, thru-transmission eddy current, ultrasonic systems, digital radiography, and acoustically excited laser vibrometry. A selection process was developed to determine the emerging NDI techniques best suited for the extended fatigue testing using the FASTER facility. The selection was based on comparison of four categories: sensitivity, ease-of-use, speed of the inspection, and fieldability. The techniques recommended for the FASTER facility testing were turbo MOI, self-nulling rotating eddy-current probes, and time varying eddy-current array sensors.

All NDI data were collected so that the signal response data can be analyzed later. Both conventional and emerging NDI technologies will be assessed to determine their field capability to detect small cracks. Results from the NDI will be compared with the crack information obtained from teardown destructive evaluations. Second layer fatigue crack detectability will be baselined with MFEC or LFEC techniques and compared with emerging inspection technologies such as MOI.

Extended Fatigue Testing

Four fuselage panels removed from the selected aircraft will be tested at the FASTER facility. The FASTER test fixture, located and operated at the FAA William J. Hughes Technical Center, shown in Figure 5, was established to assess the structural integrity of aircraft fuselage structure. The FASTER test fixture is capable of applying realistic flight load conditions including differential pressure, longitudinal, hoop and shear load in the skin, and hoop load in the frames. A full explanation of this unique test capability can be found in reference 2.

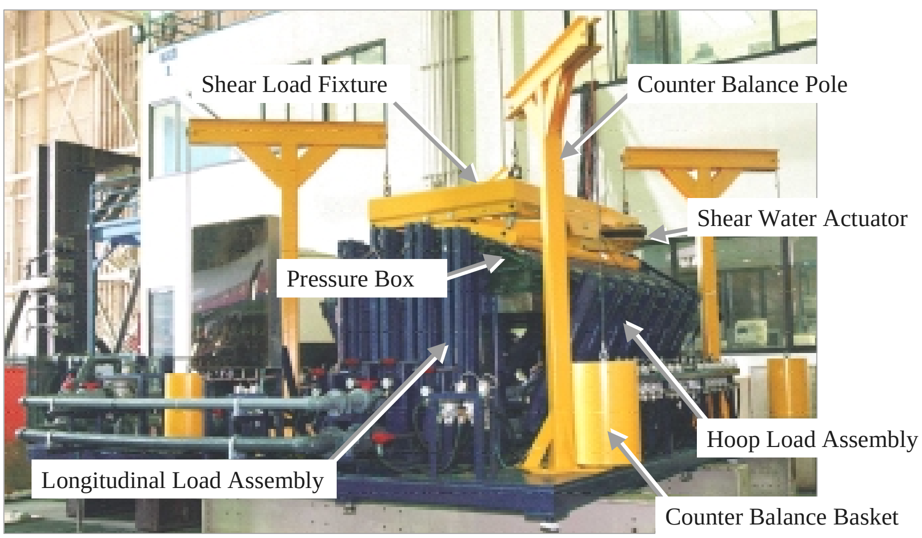

Figure 5. Full-Scale Aircraft Structural Test Evaluation and Research test fixture

The objectives of the extended testing are to (1) propagate and extrapolate the state of damage beyond one DSG; (2) characterize and document the state of damage through real-time NDI, high-magnification visual measurements, and posttest destructive evaluation of fracture surfaces; and (3) correlate analysis methods to determine crack initiation and detection, first linkup, and residual strength. To distinguish between cracks from extended fatigue testing and from service conditions, an underload marker band spectrum will be applied prior to fatigue testing.

A preliminary test plan was developed for the first fuselage panel to be tested, FT2, shown in Figure 6. The panel consists of six frames, FS- 620 through 720, and six stringers, S-2L through 7L, and contains a longitudinal lap joint along S-4L and a butt joint along FS-680. Reinforcing doublers were installed at the load applications points along the perimeter of the panel and at the ends of the frames.

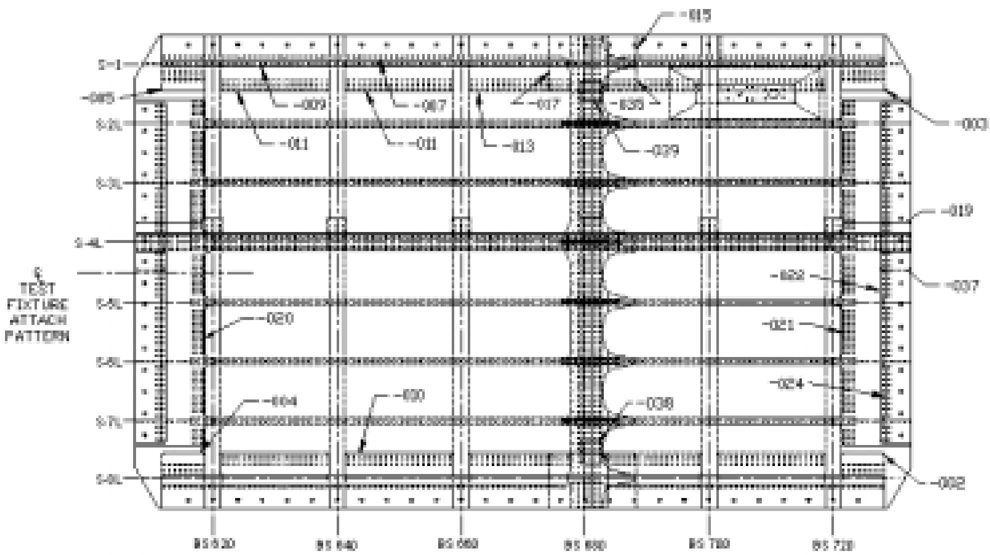

Figure 6. FT2 test panel

Geometrically nonlinear finite element analysis was undertaken to assess stresses in the B727-200 fuselage subjected to pressure and flight loads and to estimate the FASTER loads for the FT2 test panel. The loads included internal pressure applied to the skin, axial loads due to the pressure and bending, and shear loads due to the weight of the aircraft, passengers, and cargo. Shear was found to be negligible in the area of FT2. Preliminary results are shown in Figure 7.

The fuselage skin stress is due primarily to cabin pressurization and fuselage bending. The cabin pressure differential (ΔP) varies little from flight to flight and was found to be 8.6 psi based on usage history of the aircraft. On the other hand, fuselage bending is a function of maneuver, gust, and other varying loads whose frequency of occurrence is typically unknown. A preliminary load spectrum was developed based on the truncated version of the Transport Wing Structures (TWIST). The mini-TWIST is an overly aggressive spectrum for the B727 in which limit load would be unrealistically exceeded several times in single flight. Instead, it is suggested that 50% of the mini-TWIST spectrum amplitude be used, which agrees well with exceedance data measured on B737 aircraft having similar mission profile to the target aircraft in this study.

The overall test will involve three phases:

- Phase 1. Apply one of the load spectra until cracks can be measured visually. The load spectrum will include underload marker bands to assist in the striation counts during posttest fractographic examinations. Both conventional and emerging NDI will be used to document the cycles to detectable crack.
- Phase 2. Continue with the same spectrum in Phase 1 measuring crack growth to final damage state, possibly a 1.0" MSD crack or first MSD linkup, whichever occurs earlier.

- Phase 3. Determine the size and state of damage at which the residual strength requirements of 14 CFR 25.571 can no longer be met. The applied test load will be increased so that the critical condition of 14 CFR 25.571 will be applied at every cycle. The critical limit condition for lap joint MSD is 1.15ΔP plus 1g flight loads.

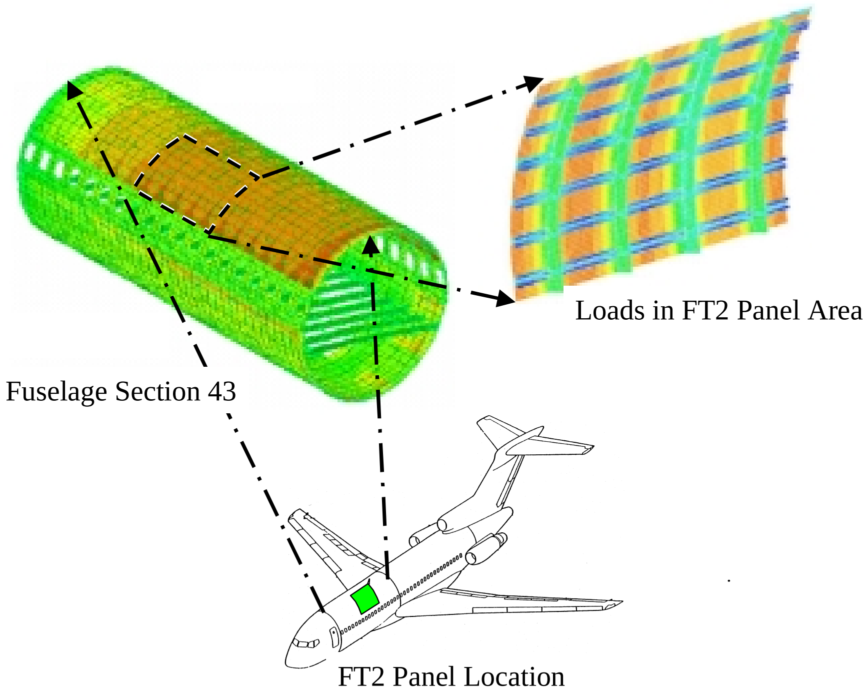

Figure 7. Finite element analysis to determine loads applied to FT2 panel

Damage Characterization

The state of damage will be characterized for all nine target structures. Samples will be prepared for fracture surface examinations using high-resolution microscope and scanning electron microscope. The extent of fatigue cracking, corrosion, faying surface fretting fatigue, and structural disbanding will be quantified through fractographic examinations. Select fastener holes will be split open to reveal the crack surfaces, and fractographic examinations will be performed to identify, catalog, and document crack initiation sites and mechanisms, crack shapes and sizes, and quality of the fastener hole surface. In addition, the crack growth histories will be empirically reconstructed using striation counts.

A teardown procedure was developed to disassemble joints and reveal fracture surfaces at fasteners as follows, Figure 8:

- Cut 1" square pieces with fasteners in the center from the joint
- Determine location of cracks around the hole via stereo microscopy, Figure 8a
- Identify region around base of fastener that can be removed without destroying cracks
- Machine two cuts through fastener-hole interface and remove fastener, Figure 8b
- Soak sample in D-limonene to soften sealant and pry open layers
- Cut slot in the plane of the crack leaving 0.05" ligament to the crack tip, Figure 8c
- Cool sample using liquid nitrogen
- Break ligament to expose fracture surface of crack, Figure 8d

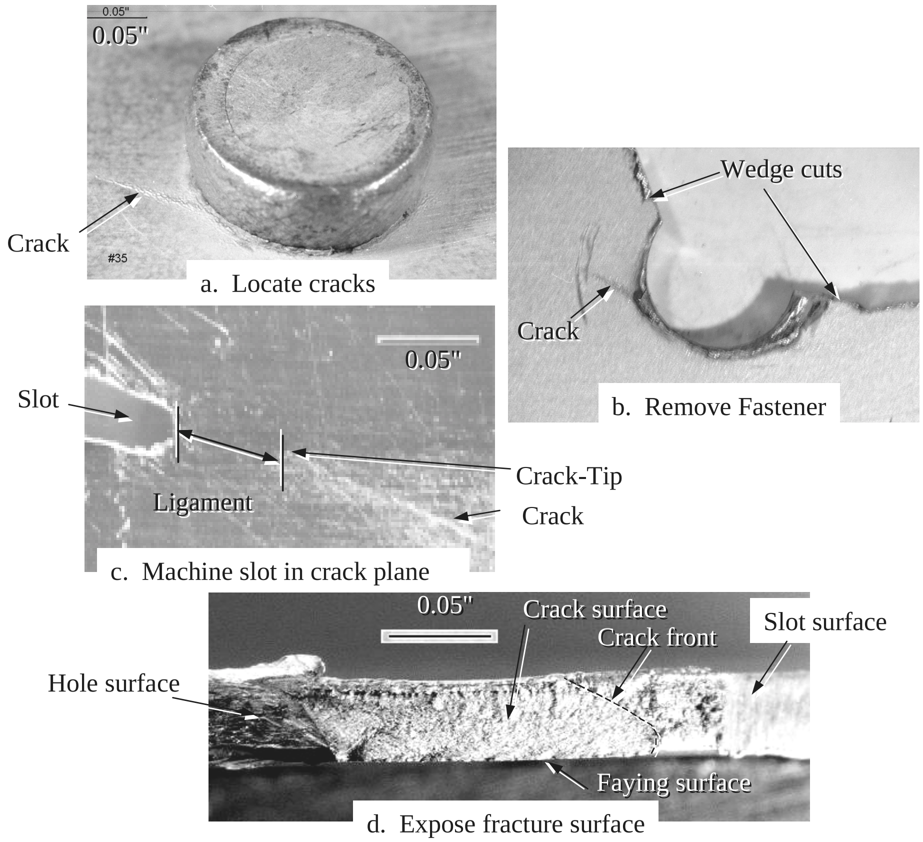

Figure 8. Steps in teardown procedure

This teardown procedure was used to characterize a section of the lap joint at stringer S-4R between fuselage stations 540 and 560, Figure 9. This section had 12 MFEC crack indications in the lower skin lower row holes, many of which had detectable cracks. Preliminary findings include the following:

- Several lower skin lower row fastener holes had more than two cracks (some had up to five) emanating from the hole
- Each crack had multiple origins
- The general direction of the cracks were normal to the hoop circumferential direction
- Crack fronts were semi-elliptic in shape with the longer side on the faying surface.
- Cracks ranged in size from 0.01" to 0.2"
- The primary origin of the cracks were at the corner of the hole and the faying surface
- While hole quality was not uniformly good, the defects in the holes were generally in the circumferential direction
- Fracture surfaces appeared to be free of corrosion and any gross mechanical rubbing damage

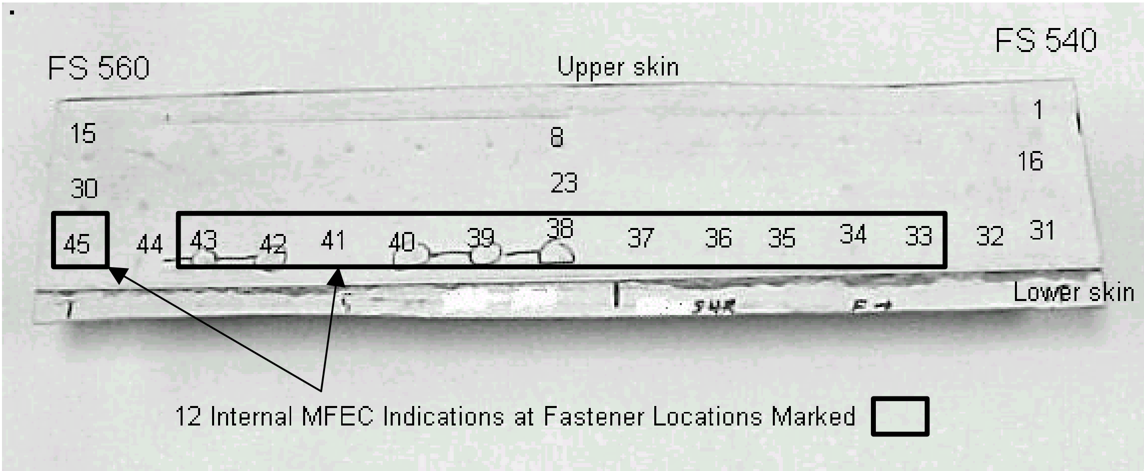

Figure 9. Lap joint section evaluated along stringer 4R

Data Analysis

The crack data (patterns, distributions, sizes, and shapes) generated will be analyzed and used to characterize MSD crack initiation, crack detection, crack linkup, residual strength, and the WFD average behavior in the structures removed. Analysis methods will be developed to correlate the state of MSD at any point in time. The following analysis steps will be undertaken, as illustrated in Figure 10:

1. *Generate Stress Spectra:* A procedure to generate stress spectra representative of prior operation and usage for each structure removed will be developed. The basic aircraft usage (e.g., flight types, flight mix, and flight hours actually flown) will be used in generating the spectra.
2. *Crack Initiation and Initial Damage Scenario:* A procedure will be determined to estimate the number of cycles to crack initiation and to estimate the size, extent, and distribution of cracks characterizing MSD initiation. Several methods will be investigated, including traditional empirical methods using extensive S-N test data with scatter factors, fracture mechanics-based equivalent initial flaw size (EIFS) concepts, and a relatively new fatigue initiation model for lap joints, Eijkhout Model, outlined in the National Aerospace Laboratory, report NLR-CR-2001-256 [3]. Using test data in a probabilistic analysis framework to determine crack initiation will also be investigated.
3. *Residual Strength and Final Damage Scenario:* The size, extent, and distribution of MSD that reduces the residual strength below predefined levels for the structure removed will be determined. Several approaches will be considered to estimate the final damage scenario, including engineering estimates using subcritical conditions and more rigorous techniques based on advanced elastic-plastic fracture criteria such as the critical crack tip opening angle and T*-integral [4].
4. *Conduct Crack Growth Analysis:* Fatigue crack growth analysis will be conducted from the initial damage scenario to the final damage scenario. Calculations will include the number of cycles to crack detection, to crack linkup, and to the final damage scenario. Government-funded or other publicly available codes and methods will be used. Standard linear elastic fracture mechanics models or advanced crack closure-based fatigue crack growth models will be considered. All methods considered will be assessed to determine the applicability and feasibility in conducting WFD assessments.

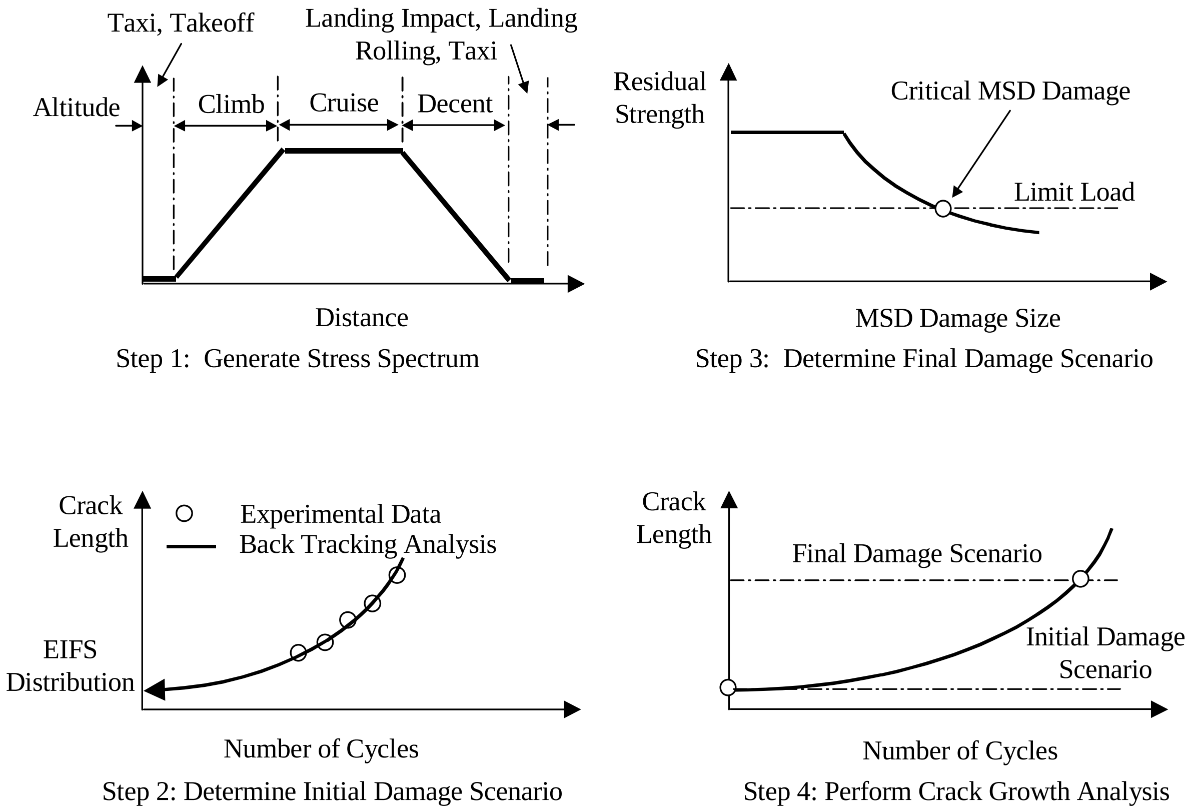

Figure 10. Schematic of analysis procedure

Significance and Output

The experience and knowledge gained from this project will enable the FAA to issue essential rules, policy, and advisory circulars pertaining to the prevention of WFD. Extended fatigue and residual strength testing of sections of actual fleet aircraft will provide data that will enable calibration and validation of prediction methodologies and will aid in evaluating the sensitivity and effectiveness of standard and emerging inspection technologies to detect small cracks.

The final output from this project will include documentation and a database containing, but not limited to, the following:

- Rational for selection of the aircraft and structure analyzed
- Procedures and data from field and preteardown inspections
- Procedures used to remove structure from the aircraft
- Procedures and approach used in the extended fatigue cycling and residual strength test using the FASTER facility
- Data and results of all inspections, including delivery of signal response data in the form of an electronic database
- Data characterizing the state of damage including:
  - Fatigue crack distributions, locations, shapes, and sizes
  - Damage initiation mechanisms and locations

  - Reconstructed fatigue crack growth histories
- Quantification of corrosion, disbonds, fretting damage at faying surfaces, and other damage
- Descriptions of the crack growth analysis methodologies used
- Results of application of the methodologies as a means to analyze crack growth
- Results of application of the methodologies as a means to predict crack growth
- Description of the methods used to determine the MSD initiation, crack detection, and crack linkup
- Results of the analysis to determine MSD initiation, crack detection, and crack linkup
- Procedure and data from material characterization
- Conclusions and recommendations specific to determination of MSD initiation, crack detection, and crack linkup

Summary

This paper summarizes the first years activities for a 3-year project involving the destructive evaluation and extended fatigue test of a retired passenger aircraft near its design service goal. The sections removed will be representative of fuselage structure susceptible to widespread fatigue damage (WFD) defined by the Airworthiness Assurance Working Group. The primary focus will be to characterize the state of multiple-site damage (MSD) in fuselage structure using detailed nondestructive inspection (NDI) and destructive examination. The state of MSD will be advanced through extended fatigue testing using the Federal Aviation Administration's Full-Scale Aircraft Structural Test Evaluation and Research facility and then assessed through NDI and destructive evaluation. The extended fatigue testing will provide data to calibrate and validate prediction methodologies and will aid in evaluating the sensitivity and effectiveness of standard and emerging inspection technologies to detect small cracks. The data generated from this effort will be used to calibrate and validate WFD assessment methods with data obtained from the analysis of real structure with natural fatigue crack initiation and accumulation of other environmental and accidental damage-induced small flaws that are representative of commercial transport use over an extended period of time (20-30 years).

References

1 Airworthiness Assurance Working Group (AAWG) report Recommendations for Regulatory Action to Prevent Widespread Fatigue Damage in the Commercial Airplane Fleet, revision A, June 29, 1999, J. McGuire and J. Foucault, Chairpersons.

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